

MARS APPROACH NAVIGATION CHALLENGES

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Abstract

The ability to accurately deliver scientific payloads to the surface of Mars is a vital part of the of the exploration of the red planet. The missions that need to take advantage of this ability are increasing and are increasingly diverse. The purpose of this paper is to describe the principles that make this process possible and show the results of applying those principles to specific mission concepts. The Mars Sample Return 2003 lander mission requires less than one degree flight path angle error and it is shown how the orbit determination and maneuver strategy result satisfy the requirement with error of $\pm 0.3^\circ$. The Mars Sample Return Netlander mission's goal is to land four probes in a specific landed network with a flight path angle constraint of $\pm 3^\circ$. The differences in approach strategies for these to mission will be identified throughout the contents of this paper with the intent of describing how the missions of the future will arrive at Mars

Introduction

As Mars exploration increases the need to deliver spacecraft accurately to the Red Planet increases. With the focus of attention being on landed systems, the need to deliver spacecraft to accurate atmospheric entry targets becomes an absolute must. The phase of Mars missions devoted to the final targeting and navigation of spacecraft entering the Mars atmosphere is being referred to in this paper as Mars approach. Mars approach can also be thought of as a process, because it encompasses the sequence of events needed for a successful Mars atmospheric entry.

The purpose of this paper is to describe this process by identifying its main characteristics and to report on the results of the process when applied to specific mission designs. The four main characteristics identified in this paper include entry flight path angle constraints, B-plane targeting, orbit determination, and maneuver strategy and execution.

Approach Characteristics

Entry Flight Path Angle Constraints

The entry flight path angle (FPA) constraint of a spacecraft's entry system is the main factor, which drives the sequence of events during the Mars approach process. The entry flight path angle constraint is also a major driver for the events after entry, because the entry FPA is constrained physically by spacecraft survivability, and scientifically by landing site accuracy.

The survivability constraints are basically in two categories, a shallow constraint and a steep constraint referring to the size of the entry FPA angle. Flight path angle is measured as the angle between the velocity vector of the spacecraft and the plane normal to the spacecraft's radial vector relative to the central body (Figure 1). The entry FPA is the above defined angle at the moment of atmospheric entry or, as used in this paper, a defined entry radius of 3522.2 km (125km altitude). An entry flight path angle of 0 deg. would mean the velocity vector is tangent to the defined sphere of radius of 3522.2 km centered on. Any negative angle would therefore enter the atmosphere.

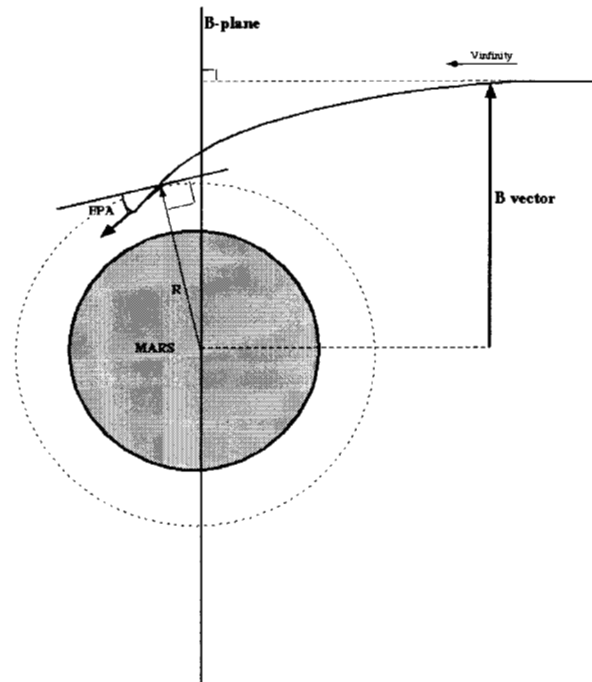


Figure 1: Flight Path Angle Diagram

In reality, there is a range of negative FPAs where the spacecraft would enter the atmosphere and then exit the atmosphere a short time later. This is an

event known as 'skip out' where the vehicle velocity is not hindered enough for gravity to pull it deep enough into the atmosphere. Therefore the vehicle passes through the atmosphere and back out into space. This is a consequence of small negative FPAs and is the reason for the shallow FPA constraint.

The steep FPA constraint is set to keep the spacecraft from entering the atmosphere with a large FPA. The larger the FPA, the more frictional heating the vehicle must endure from the atmosphere and the characteristics of the vehicle's heat shield sets an upper limit on that quantity.

There are two other constraints for landed systems, which are based on the size of the landed error ellipse. The larger the landed ellipse the higher the probability of the landing being thwarted by a large rock or slope. Scientifically, the goal is to drive the landed error ellipse as small as possible in order to be able to target smaller and smaller scientifically interesting areas. The entry FPA dispersion is a major contributor to the size of the landed error ellipse and is therefore constrained by the considerations above.

B-plane Targeting

Once the constraints are set, it is important to understand how to control the entry FPA. For interplanetary missions the navigation or targeting is done by using a plane known as the 'B-plane.' The B-plane is the plane normal to the incoming hyperbolic velocity (V_{∞} or V_{∞}) which passes through the center of the target body (Figure 1). We set a coordinate system in this plane with the origin at the target body center with the horizontal axis of the system parallel with the target body's equator (Figure 2). The horizontal axis is known as $B \bullet R$ while the vertical axis is $B \bullet T$. In this system the point where the V_{∞} vector intersects the B-plane is the B-plane target. Using this coordinate system entry targets need only be specified by specific values for $B \bullet R$, $B \bullet T$, and flight time.

The next step in controlling FPA is understanding how FPA relates to the B-plane. It turns out that for a given entry radius and incoming V_{∞} the FPA can be specified as a function of a single vector magnitude known as B . B is the vector from the coordinate system center to the B-plane target. The equation that relates B to FPA, in a two-body mechanical system, is as follows:

$$\cos(\gamma) = \frac{|B|}{r_e \left(1 + \frac{2\mu}{r_e V_{\infty}^2} \right)^{\frac{1}{2}}}$$

where γ is the FPA, r_e is the entry radius (3522.2 km), and μ the mass of the central body multiplied by the universal gravitational constant. Now for a given approach asymptote

(V_{∞}), entry radius, and FPA we can define a circle of radius equal to $|B|$ (B magnitude) in the B-plane which defines all the targets which will result in the desired FPA.

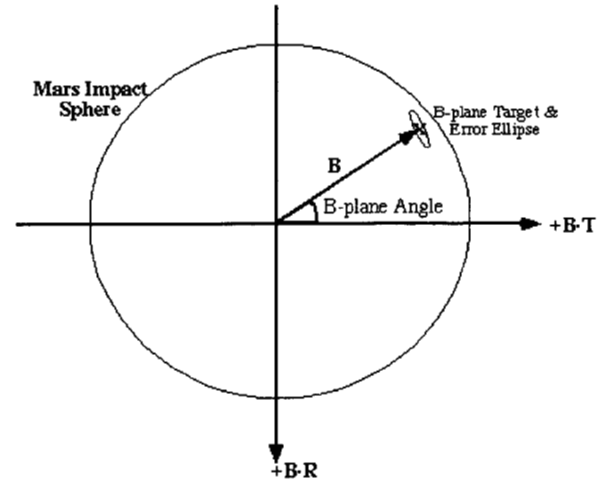


Figure 2: B-plane Coordinates Diagram

Once the magnitude of B is defined based on the FPA, the direction of B must be defined based on the latitude of the desired landing site. The direction of B can be defined by an angle measured from the horizontal B-plane axis ($B \bullet R$) to B . This angle is known as the B-plane angle. Each B-plane angle maps into an atmospheric interface latitude that is also a function of the declination of the approach asymptote. The atmospheric interface latitude in turn maps into a landing site latitude that is a function of the atmospheric descent profile.

The only thing left to specify is the time of flight or entry time. This parameter along with the atmospheric descent profile defines the landing site longitude.

Therefore, given a landing site latitude and longitude, a nominal FPA, and the characteristics of the approach asymptote the B-plane target can be calculated. The B and B-plane angle can be decomposed into components of $B \bullet R$ and $B \bullet T$ specifying a single point target in the B-plane.

Orbit Determination

Orbit determination is, obviously, a major element of approach navigation. In order to reach a given set of B-plane targets the position and velocity of the spacecraft have to be known to some fidelity. The constraint on the flight path angle is

the major contributing factor in defining the orbit determination accuracy.

Equation 1 illustrated how the FPA and \mathbf{B} are related, therefore, for a given approach trajectory, it can be seen that the FPA constraints can be mapped into constraints on the allowable uncertainty in $|\mathbf{B}|$. Through out Mars approach it is necessary to project the uncertainty in the position and velocity of the spacecraft onto the B-plane in order to evaluate the $|\mathbf{B}|$ uncertainty as well as the FPA uncertainty.

The orbit determination process uses measurements of the spacecraft's position and velocity, along with models of the forces acting on the spacecraft to determine the state of the spacecraft. Biases in the measurements and mis-modeling of the forces acting on the spacecraft add to uncertainty in the state of the spacecraft. This uncertainty is mapped onto the B-plane at the entry time and is represented by an error ellipse projected onto the B-plane and an error in the entry time.

It is the size and orientation of that the B-plane error ellipse which defines the uncertainty in the magnitude of \mathbf{B} (Figure 3). For example, if the semi-major axis of the ellipse is 30km, the semi-minor axis is 10 km, and the semi-major axis lies along \mathbf{B} (Figure 3a), then 30 km of error contributes to FPA error. Conversely, if the semi-minor axis lies along \mathbf{B} (Figure 3b) then the contribution to FPA errors is three times smaller. The orientation of the B-plane error ellipse is specified by the angle from a line through the target parallel with $\mathbf{B} \cdot \mathbf{T}$ to the semi-major axis of the ellipse where positive is in the clockwise direction. In general, the B-plane error ellipse orientation does not change much with B-plane angle; therefore, the projection of the B-plane error ellipse onto \mathbf{B} varies with B-plane angle. For example, if the orientation angle is 90° and the B-plane angle is 0° then the semi-minor axis of the ellipse lies along \mathbf{B} , and the least amount of the orbit determination error contributes to FPA error. However, if the target is changed such that the B-plane angle is 90° then the semi-major axis of the ellipse lies along \mathbf{B} , and the greatest amount of the orbit determination error contributes to FPA error. For a given Mars approach trajectory and set of OD assumption, the uncertainty in \mathbf{B} and therefore uncertainty in FPA will vary with B-plane angle or landing latitude.

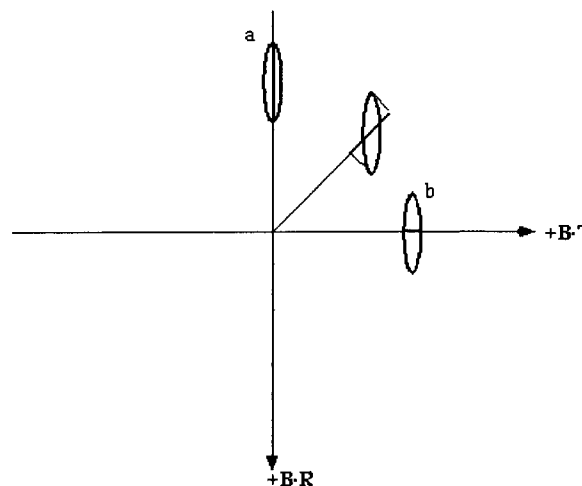


Figure 3: B-plane Error Ellipse Orientation

The two major factors that contribute to the orientation of the error ellipse are the types of measurements (data types) used for OD and the size and direction of error contributors. The most widely used data types for interplanetary navigation are radiometric data types called doppler and range. Range measures the line of site distance between the spacecraft and the measurement hardware (DSN antennae) and doppler measures the line of site velocity of the spacecraft relative to the measurement hardware. These data types only give direct information about the spacecraft in one direction, the line of sight. Only by taking many measurements over a long period of time can information in the other two directions be inferred. When using doppler and range the B-plane error ellipse tends to be oriented with the semi-major axis pointing out of the spacecraft's trajectory plane since that is the direction least measured by the data. Other data types such as VLBI can directly measure the out of plane direction and therefore changing the size and orientation of the error ellipse.

Maneuver Strategy and Execution

The maneuver strategy is designed to remove planetary protection biases as well as correct trajectory errors from the launch vehicle and other sources. Planetary protection biases and launch vehicle errors are usually dealt with by the first two trajectory control maneuvers (TCM). The remaining TCMs in the sequence usually are designed for OD/spacecraft perturbation error clean and precise B-plane targeting.

For targeting landers entry there is generally a sequence of three maneuvers during the approach phase starting at about Entry – 60 days. The first two in the sequence are generally placed to take advantage of improved OD as the spacecraft nears Mars as well as to optimize ΔV . The third of the approach sequence is typically placed within a day of entry. This maneuver's purpose is mainly for fine targeting corrections in the B-plane. Large corrections, this late in the approach phase are very costly because of the proximity to Mars, not to mention the risk of such an event. This last maneuver is taking advantage of the fact that it is close to entry because it allows little time for errors to propagate before entry. It also may allow the orbit determination to improve from seeing the Mars gravity signature in the data.

For typical maneuvers there is a large amount of time set aside for orbit determination and maneuver design (approx. 5 days). This time is not only used for the calculation of the ΔV , it is used to test the spacecraft sequence of commands and attitude profile. However for the last targeting maneuver there is a desire to use as much data, as close to Mars as possible, and so a period between data cut-off and maneuver execution of 5 days is too long. The solution to this is to design and test a suite of maneuvers well in advance, so all that has to be done is to incorporate the last bit of data in the OD process, select a "canned" maneuver and uplink it to the spacecraft. This process can reduce the time needed for maneuver design to a matter of hours (approx. 6-12 hours).

In the case where a mission's goal is to deliver a number of probes to the surface the maneuver scenario looks different. In this case, many maneuvers must be generated in the approach phase in order to target each probe to its specific entry conditions. If the goal is to accurately deliver 4 probes dispersed across the surface of Mars, there will be at least four targeting maneuvers. This takes more time; therefore, these targeting maneuvers can not be in the last day before entry. These maneuvers may be more than just fine targeting maneuvers and therefore could be costly in terms of ΔV if executed too close to entry. On other hand if the maneuvers are executed too far from entry there is more time for errors to propagate and the entry accuracy suffers. The next obstacle is time, because there has to be enough time between maneuvers to collect data and to accurately target the next probe. The approach phase for this type of mission is a constant balance between accuracy, ΔV , and time.

Mission Results

The sections below are the practical uses of the approach navigation principles that were described in the previous sections. These principles have been applied to mission scenarios and results will be reported. I have broken the sections in to the categories of Landers and Direct Entry Probes. In each section I will describe the results of the Mars approach navigation process on each type of mission

Direct Entry Landers

A Lander's atmospheric entry has unique characteristics in the approach and entry strategy. First, the nominal entry flight path usually range from -10° up to around -13° depending on entry conditions and the vehicle's ballistic coefficient. Second, the constraints on FPA are usually set at $\pm 1^\circ$ or less. Lastly, the maneuver strategies for lander entries take advantage of final TCMs close to entry, many times within 1 day before. This maneuver is used to take advantage of improved OD close to Mars and fine tune the entry targeting.

The 2003 Mars Sample Return Lander mission was the first step in the proposed Mars Sample Return Mission. Its objective was to land on Mars, collect samples, transfer the samples to a containment vessel, and launch the sample container into Mars orbit where it would wait to be picked up and brought back to the Earth by an orbiter launched in 2005. Another lander, build to print from the 2003 lander spacecraft, would be launched in the 2005 opportunity along with the orbiter. This lander would perform the same tasks as the 2003 lander and so would give the 2005 Orbiter another sample to return to the Earth **Ref. Mission Plan Paper**

The 03 MSR Lander was to be launched on a Delta II class vehicle to a type I transfer to Mars. The arrival varied over the launch period as shown in the parameters below reference to a Mars Mean Equator of Date coordinate system.

Arrival Dates: 18-DEC-2004 – 05-JAN-2004

V_∞ : 2.74 – 2.70 km/sec

DAP: 10.02° – 3.91°

RAP: -79.81° - -79.57°

These arrival conditions along with a nominal FPA equal to -12.0° set the B-plane targeting conditions. Based on equation 1 the $|B|$ to reach these targets at an entry radius of 3522.2 km is equal to 7100 km and 7163 km for the open and close cases of the launch period respectively. With the above arrival conditions we can also calculate how errors in $|B|$ map into errors in FPA. Using EQUATION 1 again we find that 1° FPA is approximately 26.6 km along B. This value will determine whether our orbit determination accuracy meets the imposed flight path angle constraint.

In order to discuss the OD accuracy of the approach phase, it is important to understand some of the aspects of the spacecraft design. The two biggest issues of the spacecraft design are the attitude control mechanisms and the maneuver execution errors. The Lander was designed to utilize three axis stabilization,

using thrusters. This means that the lander would maintain attitude by pulsing thrusters when it reached one limit of the attitude control constraints. Due to thruster misalignment and thrust variation this pulsing perturbs the trajectory and induces uncertainty into the OD. The maneuver execution errors from TCMs induce OD error in the same fashion. The difference is the attitude control thrusters add very small amounts many times over the trajectory which if not accounted for adds up to a large perturbation. The TCM error is more discreet on a larger scale and is easier to account for.

The above spacecraft perturbations along with amount and quality of the data measured, and the fidelity of models such as solar pressure, Earth orientation/timing parameters, and Mars ephemeris all contribute to the OD and how it matures along the trajectory. Figure 4 shows the OD accuracy history from Entry - 60 days until entry for the 2003 MSR Lander. This figure plots the axes of the B-plane error ellipse as well as the uncertainty in **B** as a function of time. The spike in the OD at Entry - 10 days corresponds to error introduced by a TCM. Figure 5 plots the same information focusing on the last day before entry and identifies the level of OD knowledge during that time.

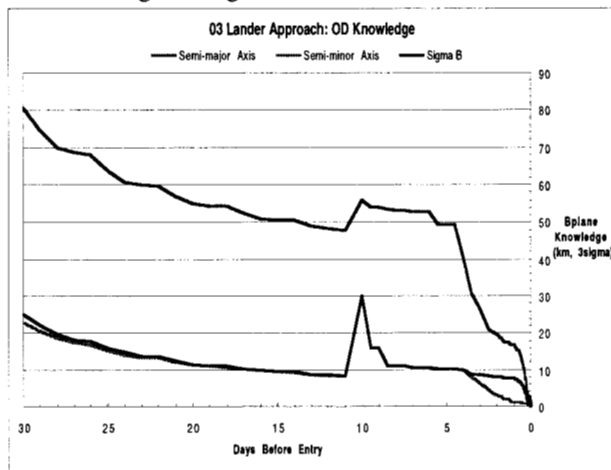


Figure 4: Lander OD Knowledge History Plot (Days Before Entry)

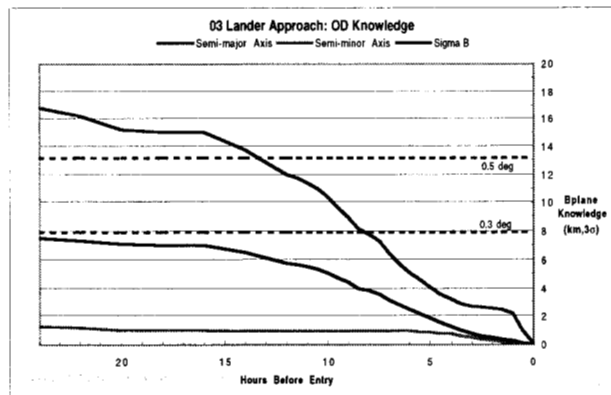


Figure 5: '03 Lander OD Knowledge History Plot (Hours Before Entry)

Figures 4 and 5 along with the FPA constraint define the placement of the last TCM. Setting an FPA requirement of $\pm 3^\circ$ forces the knowledge level to be better than 8km such that the maneuver execution errors after the last maneuver do not bump the uncertainty up over the constraint. If the data cut-off is set at Entry - 18 hours $|\mathbf{B}|$ is known to 7km (3σ) which maps into just over 0.25° of FPA. Taking an average size last maneuver of 1 m/sec with 2% proportional and 10 mm/sec fixed magnitude execution error per axis along with a 10 mm/sec fixed pointing error gives 24 mm/sec of error per axis. Propagate this error for 12 hours contributes 1.1 km of error in all directions and most importantly along **B**. Combining the error from a maneuver at Entry - 12 hours with the $|\mathbf{B}|$ knowledge at Entry - 18 hours (allowing 6 hours for the OD process, "canned maneuver selection", and sequence uplink) gives a total uncertainty or "delivery" of 7.1 km along **B** which maps to $\pm 0.27^\circ$ of FPA uncertainty. Now since this meets the requirement of $\pm 3^\circ$ it is a good placement for the last TCM.

As described in the previous section the uncertainty in $|\mathbf{B}|$ depends upon the orientation of the B-plane error ellipse and landing site target. This means that for a given trajectory and set of OD assumptions the semi-major and minor axes set the limits of the knowledge of **B**. Table 1 shows the delivery from the final maneuver at Entry - 12 hours for B-plane angles of 0.64° and 26.7° corresponding to landing sites at 5° north and 15° south latitude. It can be seen in the table that the error ellipse basically, remains unchanged along with the orientation angle, ϕ , but the resulting **B** and FPA uncertainty is much higher for the 5° north case. Figure 6 shows the error ellipse orientations in the B-plane for both cases. The MSR project had as a science goal to be able to access a latitude landing band from 15° south to 15° north between the 2003 and 2005 landers. Table 1 and Figure 6 show how the Nav accuracy biases the 2003 landing sites to the south. It turns out that the 2005 landing sites are biased north by the Nav accuracy. On top of the Nav bias in the landing site, there are power preferences on landing site which for the '03 and '05 lander missions match the Nav preferences. Therefore, the '03 landing band was set to be from 15° south to 5° north while the '05 landing band took up the slack from 5° north to 15° north.

03 Lander Last Maneuver Delivery Summary					
=> OD Cut-off @ Entry - 18 hours, TCM4 @ Entry - 12 hours					
Landing Latitude	SMAA	SMIA	φ	σ_B	σ_{FPA}
(deg)	(km, 3s)	(km, 3s)	(deg)	(km, 3s)	(deg, 3s)
5	14.7	1.9	118.1	7.0	0.3
-15	15.6	1.9	116.7	1.9	0.1

Table 1: '03 Lander Last TCM Entry Error

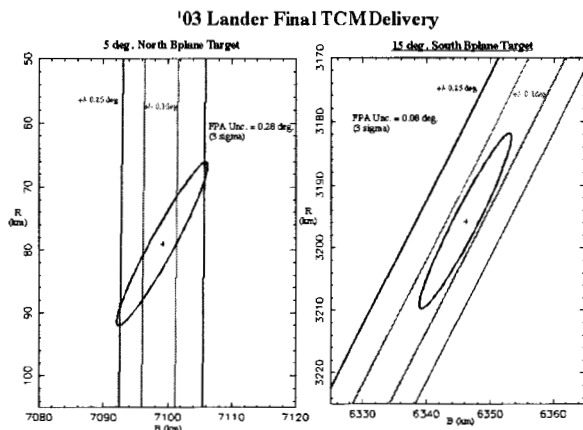


Figure 6: '03 Lander Error Ellipse Orientation for 5° North and 15° South Landing Sites

Multiple Direct Entry Probes

The approach phase involved with delivering multiple probes to the surface of Mars differs significantly from that of the lander approach phase. A sequence of four deployments can force the first targeting maneuvers and releases to be as early as Entry - 30 days. The reason for this is that there might have to be four separate targeting and release strategies to access four distinct landing sites. In general, probes tend to be lighter therefore sustain ballistic coefficients which allow steeper flight path angles, ranging from about -15° to -20° . Although the goal is to deliver them as accurately as possible, the FPA constraints for probes tends to be in the range of ± 2 or ± 3 degrees.

The Mars Sample Return mission incorporated a a French Space Agency (CNES) probe mission called the Netlander mission. This mission's goal was to deliver four 60 kg probes, called Netlanders, dispersed on the surface of Mars to perform for seismic, atmospheric and other measurements. The science objectives called for the probes to be dispersed in longitude and latitude forming a specific landed network. As long as the Netlanders were spaced properly there landed delivery accuracy was not critical. The main driver for the FPA accuracy of $\pm 3^\circ$ was atmospheric entry, descent and

landing survivability. The flight path angle constraint was broken into specific allocations; a Nav component and a release mechanism component. The release mechanism was allocated $\pm 1^\circ$ while the Nav system was allocated $\pm 2^\circ$ making the assumption these errors were independent¹. The approach navigation goals were to target the probes to meet the landed network requirements using no more than 50 m/sec of ΔV , to deliver the probes to the atmospheric entry point with less than a $\pm 2^\circ$ FPA error, and operate this whole strategy with no disruption to the subsequent Mars Sample Return mission.

The main constraints, which drive the maneuver and release schedule, are FPA accuracy, ΔV allocation, and time. The closer to arrival the Netlanders are targeted and released the better their entry accuracy, but the later the probes are targeted the higher the targeting maneuver ΔV s. The time constraints are set by defining the amount of time needed to collect data of OD, design targeting maneuvers, and uplink and execute the maneuver release sequence.

The first time constraint levied stated that all the Netlander activity must be completed and the orbiter targeted for aerocapture by Entry - 10 days. This constraint was set to allow time for the orbiter to prepare for aerocapture entry. It was decided to allow 2 days after the last Netlander deployment for OD, design, and execution of the first aerocapture target maneuver. This meant that all Netlander activity must be completed at or before Entry - 12 days.

The FPA accuracy constraint indirectly sets a maximum time from entry constraint. It was assumed for the Netlander mission that the first probe would be targeted to entry from the time of TCM3 at Entry - 60 days. From that point on, nothing can be done until the Nav accuracy matures to the point where it meets the necessary FPA requirements for the first Netlander. Based on doppler and ranging data a preliminary run showed the OD knowledge would satisfy the requirement at Entry - 25 days. From Entry - 25 days to Entry - 24 days a trim maneuver would be designed based on OD to correct for errors and the maneuver would be executed. Four hours after the execution of the trim maneuver, the probe would be released. The FPA requirement along with the Entry - 12 days time constraint set the time interval available for the deployment of the next three probes. This 12 day interval allows for four days for each Netlander sequence. Each Netlander sequence consists of performing an initial entry target maneuver, subsequent OD, design a trim maneuver to clean up errors, and release the probe. The trim maneuver is

needed because the errors introduced by the initial target maneuvers are large and do not meet the FPA requirement, so additional OD along with a trim maneuver were added to clean up the initial targeting errors. The overall maneuver and probe release schedule can be seen in (Figure7).

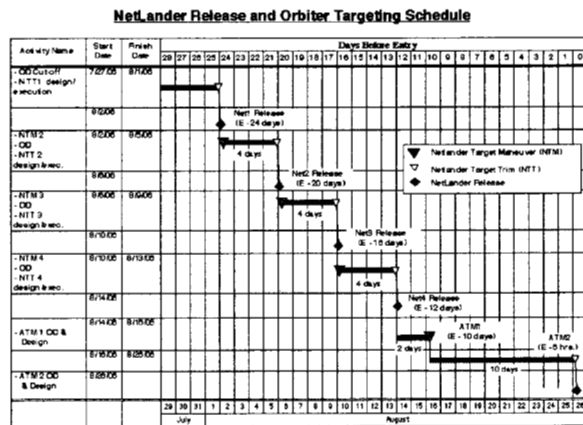


Figure 7: Netlander Maneuver and Release Schedule

In order to save time it was decided to design trim maneuvers simultaneously with the next Netlander target maneuver. A single Netlander sequence would go as follows:

1. Execute probe 2's target maneuver, called Netlander Target Maneuver 2 (NTM 2)
2. Collect data for ≈ 2 days
3. Perform the OD process
4. Design Netlander Target Trim 2 (NTT 2) maneuver along the next Netlander target maneuver (NTM 3)
5. Uplink maneuver and release sequence
6. Release probe 2.

A detailed schedule of the Netlander sequence can be seen in (Figure 8). The figure shows that it would be difficult to squeeze the Netlander sequence into a smaller amount of time.

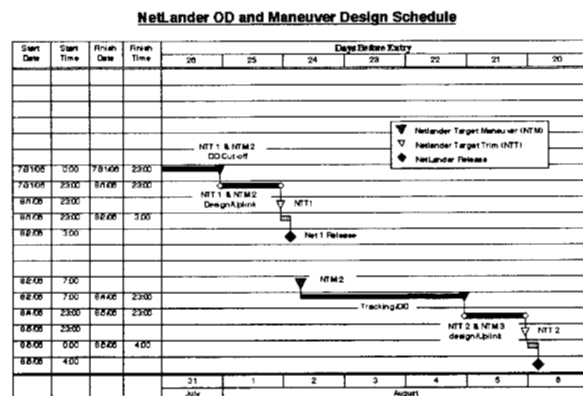


Figure 8: Netlander OD & Maneuver Design Schedule

As described earlier the landing sites and corresponding B-plane targets have a significant impact on the FPA accuracy. The question is whether or not the landing sites can be chosen such that they satisfy the network and FPA constraints. The high level goal of the Netlander scientists was to set up a network of three Netlanders on one side of Mars and the fourth on the opposite side. For navigation this generally means three prograde entries (B-plane angles from 270° to 90°) and one retrograde entry (B-plane angle between 90° and 270°). The prograde Netlanders should form a triangle with spacing of at least 30° in latitude/longitude¹. On top of the network constraints, the landing sites had to meet certain constraints of altitude and pressure, which was ultimately completed by the team of Netlander scientists². From the preliminary OD analysis of Netlander delivery it was found that the orientation of the B-plane error ellipses would be around 60° and therefore the FPA uncertainty would favor prograde B-plane angles of $270^\circ - 0^\circ$ (quadrant IV) and retrograde B-plane angles of $90^\circ - 180^\circ$ (quadrant II). The network could only accommodate this with two prograde sites in quadrant IV with 30° of longitude separation and one in quadrant II satisfying the opposing landing site. The fourth landing site was placed in quadrant I completing the triangle of sites on a single side with 30° of latitude separation. An example landing site network can be seen in Figure 9, while the corresponding B-plane targets can be seen in Figure 10. Notice in Figure 10 how the Netlander targets 2,3 and 4 are orientated in favorable quadrants while Netlander 1 is not.

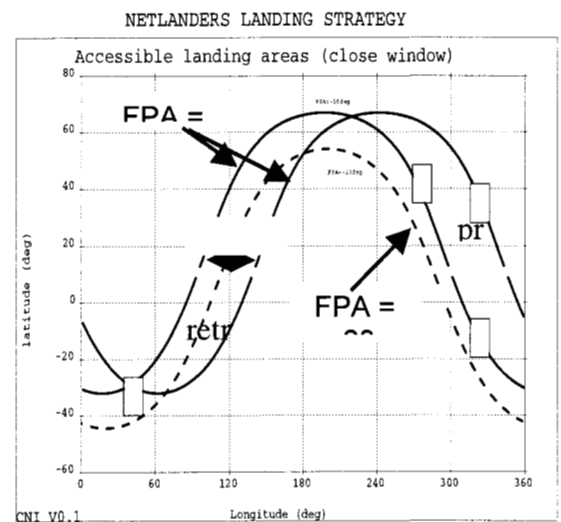


Figure 9: Example Set of Netlander Landing Sites

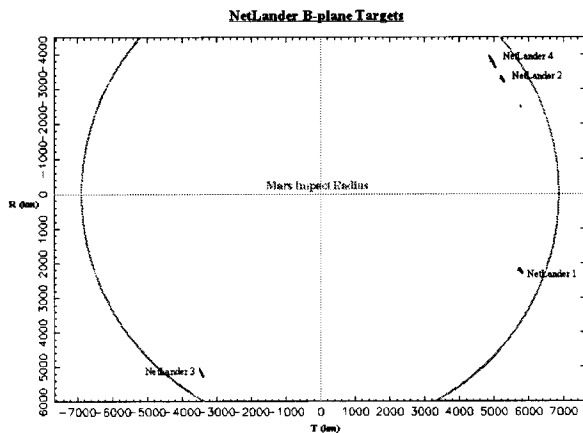


Figure 10: Netlander B-plane Targets

Figure 10 shows how the Netlander targets are spread in B-plane angle and latitude, but it does not show the spread in longitude. The longitude of the landing sites is controlled by the arrival time or time of flight (TOF). By changing the time of flight of the trajectory, one changes the arrival time of the probes which changes the longitude of the landing site because of the rotation of Mars. Two TOF maneuvers were incorporated into the targeting maneuver strategy. A time of flight change was added for the targeting maneuver of Netlander 3 in order to reach the desired landing site chosen by the scientists. A two hour time of flight change was needed to change the arrival time of Netlander 3 in order to land at a longitude $\approx 30^\circ$ further east of the original trajectory. This 2 hour change at Entry - 20 days costs approximately 13 m/sec and adds OD uncertainty due to maneuver execution errors. A second TOF maneuver was incorporated to target Netlander 4. This maneuver was needed to target the corner of the triangle network that was separated at least 30° in longitude. This TOF change at Entry - 16 days costs 16 m/sec of ΔV and also adds OD uncertainty. The time of flight maneuvers are combined with the B-plane changes for optimal performance.

The overall targeting schedule starts by targeting Netlander 1 to its nominal entry in quadrant I. Next Netlander 2 is targeted in quadrant IV with the same arrival time and close in longitude as Netlander 1, but to a specified landing site at least 30° north. Netlander 3 is targeted to a B-plane target in quadrant II combined with a 2 hour TOF change to reach its target. Finally Netlander 4 is targeted back to quadrant IV close in latitude to Netlander 2 but to a specified landing site separated by another 2 hour TOF change. Therefore Netlander IV is separated by approximately 60° deg. in longitude (4 hours TOF change). Table 2 shows the ΔV sizes for each target and trim maneuver.

Maneuver	Delta V (m/s, 99%)
NTT 1	0.07
NTM 2	2.70
NTT 2	0.09
NTM 3 - 2hrsTOF	15.30
NTT 3	0.16
NTM 4 - 2hrsTOF	19.21
NTT 4	0.26

Table 2: Netlander Maneuver ΔV s

Each time a maneuver is executed the execution errors of that maneuver add trajectory error. The OD process must add uncertainty to the known state of the spacecraft in order to account for the maneuver execution errors, until sufficient data is collected and the maneuver can be estimated well. The amount of uncertainty added to the OD is specified by the size of the maneuver execution errors. The MSR orbiter spacecraft team calculated that the Netlander maneuvers would be execute to the level shown in Table 3, based on there ΔV size. Figure 11 shows the OD B-plane uncertainty ellipse size as a function of time on Mars approach. The addition of error due to maneuvers, based on the maneuver execution in Table 3, is identified by the spikes in the knowledge of the semi-major and minor axes. The lines with no spikes represent the OD knowledge with out any maneuver errors. The error from Netlander 1 trim maneuver is negligible and doesn't show up on the graph compare to the OD error. The initial target maneuver for Netlander 2 shows some knowledge degradation, but does not compare with the spikes due to Netlander's 3 and 4 maneuver spikes. The large error from Netlanders 3 and 4 is due to the proportional errors of the large time of flight maneuvers.

	$\Delta V \geq 1 \text{ m/s}$	$0.2 \text{ m/s} < \Delta V < 1.0 \text{ m/s}$	$0.004 \text{ m/s} < \Delta V < 0.2 \text{ m/s}$
Proportional Magnitude	0.6%	2.0%	2.0%
Fixed Magnitude	2 mm/s	2 mm/s	2 mm/s
Proportional Pointing (per axis)	5 mrad	10 mrad	10 mrad
Fixed Pointing (per axis)	5 mm/s	5 mm/s	5 mm/s

Table 3: Maneuver Execution Error per ΔV Size

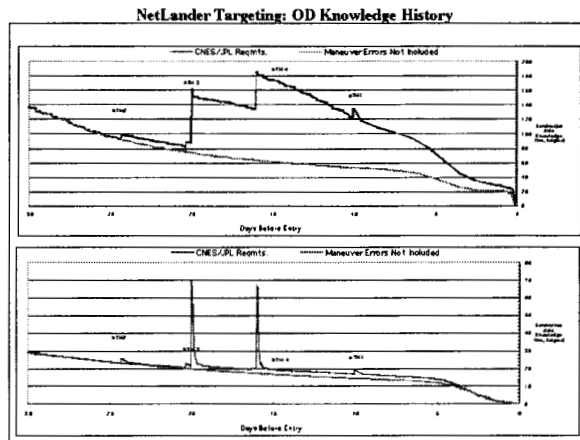


Figure 11: Netlander OD Knowledge History

The results of delivery of each Netlander from each maneuver due to the combination of orbit determination and maneuver execution errors can be seen in Table 4. The table shows that the delivery of Netlander 1 from its Netlander Target Trim (NTT) maneuver does not meet the $\pm 2^\circ$; therefore, our initial assumption that the OD would be sufficient at Entry - 24 days to deliver Netlander 1 was incorrect. Moving the targeting and release of Netlander 1 closer to Entry is not a solution because that would not leave enough time to deliver the rest of the Netlanders before Entry - 12 days. One option is to move the B-plane target and landing site further north so the error ellipse orientation is more favorable to flight path angle. The delivery of Netlander 2 satisfies the requirement easily. This is due to the fact that its B-plane target and ellipse orientation are such that the semi-minor axes lines up with **B**, the FPA direction. It is also due to the fact that the Netlander Target Maneuver (NTM) for Netlander 2 does not have a time of flight change and therefore is sufficiently small. Netlanders 3 and 4 both do not meet the FPA requirement because the large time of flight maneuvers are driving the OD uncertainty too high. The landing sites must be evaluated again to set up the network with less longitude spacing in order to make this strategy work. All this analysis was done assuming the use of doppler and range data only. An option that could improve the deliveries of all the Netlanders is the use of another data type such as Δ V/LBI. One struggle with this data type would be the scheduling of measurements. These measurements must be taken during DSN complex overlaps with the use of one station at each complex. The maneuver and release schedule would have to be reworked to be consistent with these overlaps, although improved accuracy may provide the flexibility needed to make such a scenario work.

Maneuver	SMAA (km,3 σ)	SMIA (km,3 σ)	B (km,3 σ)	FPA Unc (deg,3 σ)
NTT 1	105.1	28.9	85.6	2.8
NTM 2	122.3	69.7	69.7	2.3
NTT 2	106.4	25.1	25.2	0.8
NTM 3 - 2hrsTOF	174.3	139.2	149.0	4.8
NTT 3	148.8	19.6	71.5	2.3
NTM 4 - 2hrsTOF	196.6	138.1	140.4	4.6
NTT 4	162.4	18.0	31.8	1.0

Table 4: Netlander Delivery Results

Conclusion

Mars approach navigation can take on very different looks depending on the goals of the mission, but the principles remain the same. The spacecraft system requirements in the form of a set of survivable flight path angle constraints along with the science goals of the mission, in the form of landing sites, drive the approach strategy. No matter if the last maneuvers are within a day of entry or twenty days of entry the combination of the size and orientation of the orbit determination error along with the size and performance of the maneuvers must meet the entry target requirements.

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